

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></p>					
1. REPORT DATE 8 Jun 04	2. REPORT TYPE Final Technical Report	3. DATES COVERED (From - To) 3 Apr 00 - 2 Apr 03			
<b>4. TITLE AND SUBTITLE</b> Nanostructured Functional and Multifunctional Materials			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER N-00014-00-1-0476		
			5c. PROGRAM ELEMENT NUMBER		
<b>6. AUTHOR(S)</b> Lieber, Charles, M.			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> The President and Fellows of Harvard College Office for Sponsored Research, 1350 Mass. Ave, Suite 700 Cambridge MA 02138			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>		
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Office of Naval Research Ballston Centre Tower One 800 N. Quincy Street Arlington, VA 22217-5660			<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ONR		
			<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>		
<b>12. DISTRIBUTION AVAILABILITY STATEMENT</b> Approved for Public Release; distribution is unlimited.			<b>BEST AVAILABLE COPY</b> <b>20040615 093</b>		
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> <p>This project is focused on developing the underlying science and technology required to enable the rational design and synthesis of functional nanoscale assemblies and the hierarchical assembly of these local functional structures into multifunctional systems. To achieve these objectives we are pursuing a highly interdisciplinary program that addresses in parallel the major scientific hurdles of the project, including development of electronically and optically well-defined nanoscale building blocks required to create novel functional nanostructures, and development of flexible and scalable methods for the assembly of these building blocks into novel functional nanostructures and nanostructured multifunctional systems. Significant progress has been made during the past fiscal year in several areas of the project. First, we have developed and demonstrated powerful methods for creating the first axial nanowire superlattice structures in which both composition and doping can be varied; Second, we have demonstrated that the nanowire possess novel photonic behavior and have configured optical bar codes and intrawire nanoscale light-emitting diodes. Third, we have demonstrated that doping modulation can be used to design and synthesize active nanoelectronic devices. These nanowire super lattice materials open up many new opportunities in nanoelectronics and nanophotonics.</p>					
<b>15. SUBJECT TERMS</b> Nanowires; assembly; nanostructures; multifunctional systems; nanoelectronics; nanophotonics					
<b>16. SECURITY CLASSIFICATION OF:</b> a. REPORT    b. ABSTRACT    c. THIS PAGE		<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b> 19	<b>19a. NAME OF RESPONSIBLE PERSON</b> Mary Mitchell <b>19b. TELEPHONE NUMBER (Include area code)</b> (617) 495-5501	

Final Technical Report  
ONR Grant No. N-00014-00-1-0476  
P.I. Professor Charles M. Lieber

## Nanostructured Functional and Multifunctional Materials

### **Part One.**

#### **ONR Program Officer: Dr. John Pazik**

#### **Program Objectives.**

The major goals of our proposed studies are to develop the underlying science and technology required to enable the rational design and synthesis of functional nanoscale assemblies and the hierarchical assembly of these functional structures into multifunctional nanosystems. Our specific objectives are (1) to develop new nanoscale building blocks to create novel functional nanostructures, (2) develop methods and define fundamental nanoelectronic, photonic and mechanical properties of the nanoscale building blocks and (3) to develop general methods for the assembly of functional units into nanostructured multifunctional systems.

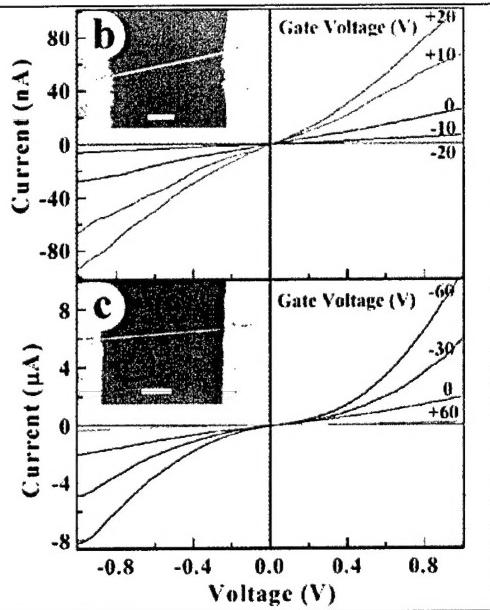
#### **Technical Summary.**

To achieve these objectives we pursued a highly interdisciplinary program that addressed in parallel the major scientific hurdles of the project, including development of electronically and optically well-defined nanoscale building blocks required to create novel functional nanostructures, development and implementation of characterization methods needed to define fundamental physical properties of the building blocks, and development of flexible and scalable methods for the assembly of these building blocks into novel functional nanostructures and nanostructured multifunctional systems.

### **SYNTHESIS OF NANOSCALE BUILDING BLOCKS.**

**Synthesis of nanowires with controlled electronic properties.** We have extended in a significant way our synthesis/growth methods to enable reproducible doping of semiconductor nanowires. Single crystal InP NWs with n- and p-type doping were prepared by laser-assisted catalytic growth (LCG). Field emission scanning electron microscopy (FE-SEM) images of the doped NWs demonstrate that the wires extend up to tens of micrometers in length with diameters on the order of 10 nanometers and TEM has demonstrated that the doped NWs are single crystals with  $<111>$  growth directions. To confirm the presence and type of dopants in the NWs, we used gate-dependent, two terminal transport measurements on individual NWs, since the conductance will respond in an opposite way to changes in gate voltage ( $V_g$ ) for n-and p-type NWs:  $V_g > 0$  will lead to an accumulation of electrons and increase in conductance for n-type NWs, but will deplete holes and reduce conductance for p-type NWs. Figure 1 shows the typical gate-dependent current-voltage (I-V) curves obtained from individual Te- and Zn-doped NWs respectively. The I-V curves are linear or nearly linear for the NWs at  $V_g = 0$ , indicating the

**Figure 1.** Doping and electrical transport of InP NWs. **b** and **c**, Gate-dependent I-V behavior for Te- and Zn-doped NWs, respectively. The insets shows the NW measured with two terminal Ni/In/Au contact electrodes. The scale bars correspond to 1  $\mu$ m. Specific gate-voltages used in the measurements are indicated on the right hand sides of the figures on the corresponding I-V curves. Data were recorded at room temperature.

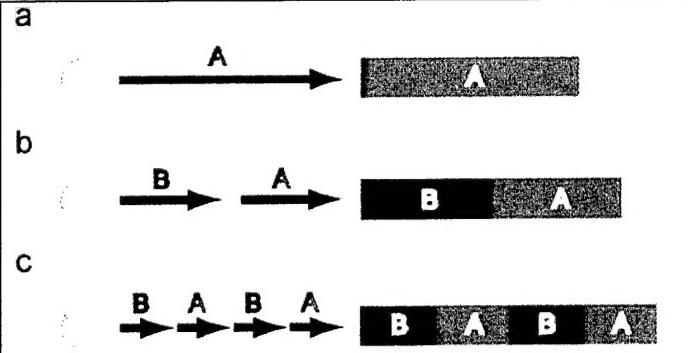


metal electrodes make ohmic contact to the NWs. The transport data recorded on Te-doped NWs show an increase in conductance for  $V_g > 0$ , while the conductance decreases for  $V_g < 0$ . These data clearly show that Te-doped InP NWs are n-type. Gate-dependent transport data recorded on Zn-doped NWs show opposite changes in conductance with variation in  $V_g$ : for  $V_g > 0$ , conductance decreases and for  $V_g < 0$  conductance increases, and thus demonstrate that the Zn-doped InP NWs are p-type. Significantly, similar results have also been obtained by our group for silicon nanowires (SiNWs); that is, both n-type and p-type SiNWs have been reproducibly synthesized.

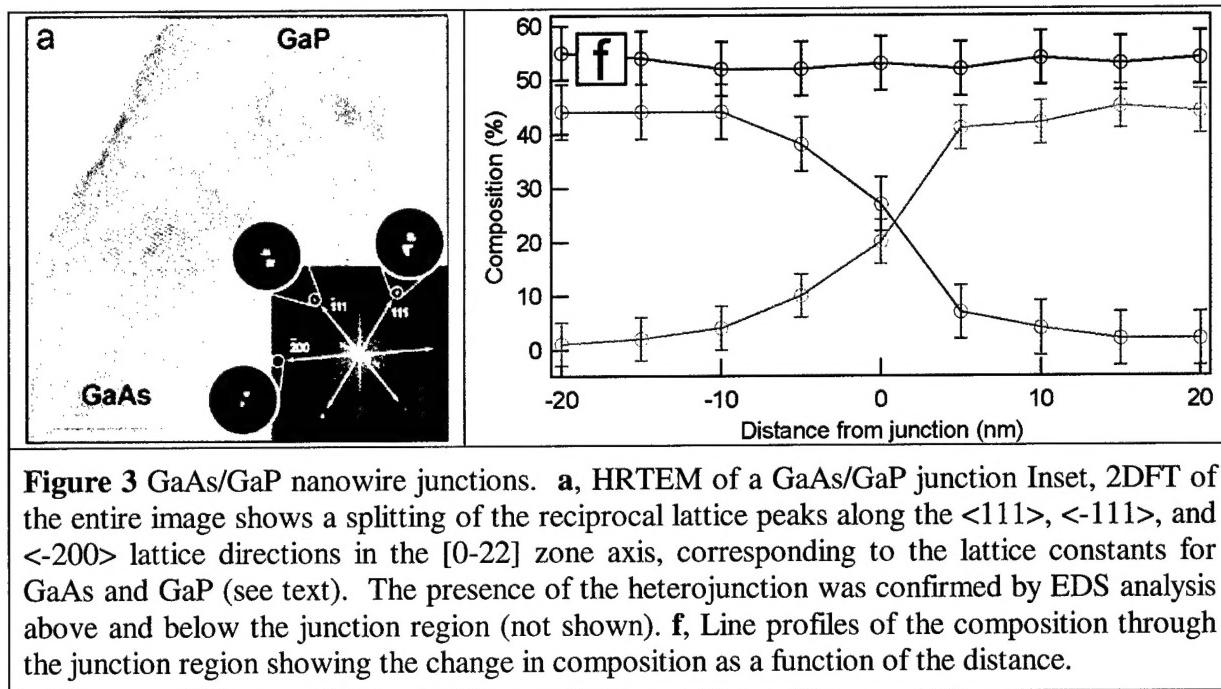
These results are of great significance since they demonstrate for the first time that the electronic properties of a nanomaterial can be reproducibly controlled during synthesis (in contrast to carbon nanotubes), and thus open up the opportunity for creating complex functional devices through the assembly of the electronically distinct nanowire building blocks.

**Nanowires axial superlattices.** A major breakthrough was made with our development of a general approach for growing single crystal nanowire axial superlattices. This work utilized previous knowledge developed in ONR program, where we shown that nearly monodisperse metal nanoclusters can be used to control the diameter and through growth time the length of group III-V and IV semiconductor nanowires via a vapor-liquid-solid growth process. The underlying concept we developed is outlined in Figure 2.

**Figure 2.** Synthesis of nanowire superlattices. **a**, A nanocluster catalyst (gold) nucleates and directs nanowire (blue) growth with the catalyst remaining at the terminus. **b**, Upon completion of the first step, a different material (red) can be grown from the end of the nanowire. **c**, Repetition of steps **a** and **b** leads to a superlattice.



To create a single junctions within the nanowire, the addition of the first reactant is stopped during growth, and then a second reactant is introduced for the remainder of the synthesis; repeated modulation of the reactants during growth produces nanowire superlattices. This new idea has been demonstrated in the growth of superlattices consisting of compositional modulation (GaAs/GaP), which have been characterized in detail by analytical high-resolution transmission electron microscopy (Fig. 3).



**Figure 3** GaAs/GaP nanowire junctions. **a**, HRTEM of a GaAs/GaP junction Inset, 2DFT of the entire image shows a splitting of the reciprocal lattice peaks along the  $\langle 111 \rangle$ ,  $\langle -111 \rangle$ , and  $\langle -200 \rangle$  lattice directions in the [0-22] zone axis, corresponding to the lattice constants for GaAs and GaP (see text). The presence of the heterojunction was confirmed by EDS analysis above and below the junction region (not shown). **f**, Line profiles of the composition through the junction region showing the change in composition as a function of the distance.

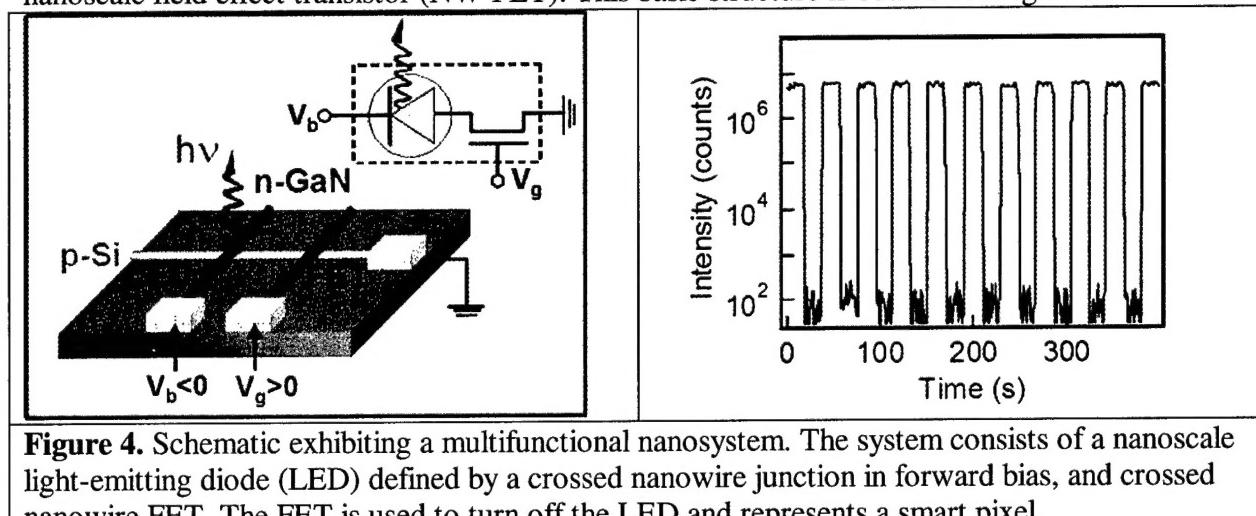
In addition, similar studies have been carried out in superlattice defined by doping modulation(p-Si/n-Si and n-InP/p-InP). Overall, these materials open up the possibility of studying a wide-range of electronic and photonic phenomena.

## FUNCTIONAL NANOWIRE DEVICES

**Demonstration of Nanowire Axial Superlattices for Nanophotonics.** We have developed measurement technology and used this instrumentation to characterize unique electronic and photonic properties of the nanowires with composition and doping modulation. GaAs/GaP nanowire superlattices are an attractive system to explore for nano-photonic applications since GaAs is a direct band gap semiconductor, while GaP has an indirect gap. Indeed, photoluminescence (PL) imaging of individual nanowire superlattice structures shows that these nanowires exhibit an emission pattern consistent with emission originating from the GaAs regions, separated by dark GaP regions that act as optical “spacers.” The GaAs regions also exhibit a strong polarization, which might be useful in several types of applications. For example, in their present form these nanowire superlattice structures could be exploited as optical nano-barcodes, and moreover, the wide range of group III-V and II-VI nanowires that have been demonstrated by our group suggests that it should be possible to encode additional information through variations in the color of the emitting region using multi-component superlattices. Using materials with a large dielectric contrast might also enable the creation of 1D waveguides with built-in photonic band gaps, or as cavities for nanowire lasers. These are all important directions to pursue for the future.

**Demonstration of Nanowire Axial Superlattices for Nanoelectronics.** In addition, we fabricated p-n junctions within individual silicon nanowires by nanocluster catalyzed chemical vapor deposition and dopant modulation. The ability to synthesize modulation doped nanowire superlattices opens up new opportunities ranging from ultra-sensitive biological and chemical detectors to bipolar transistors and highly integrated logic gates for nanoelectronics. Moreover, the direct growth of modulation-doped nanowires eliminates the lithographic steps used to create doped nanotube p-n junctions and thus facilitates the bottom-up assembly of complex functional structures when combined with recent advances in the directed *en masse* organization of nanowire structures.

**Demonstration of a Multifunctional Nanosystem.** Lastly, we have made another breakthrough with the first demonstration of an assembled multi-functional nanosystem, where the structure integrates by bottom-up assembly a nanoscale light-emitting diode (nanoLED) and a nanoscale field effect transistor (NW-FET). This basic structure is outlined in Figure 4.



**Figure 4.** Schematic exhibiting a multifunctional nanosystem. The system consists of a nanoscale light-emitting diode (LED) defined by a crossed nanowire junction in forward bias, and crossed nanowire FET. The FET is used to turn off the LED and represents a smart pixel.

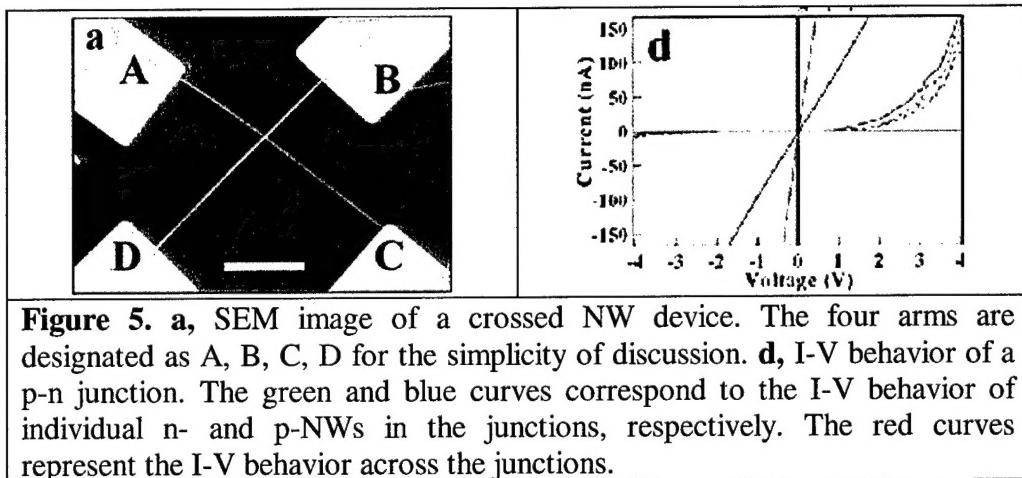
With increasing voltages to the gate nanowire, the current level and output light intensity of the LED rapidly decreases. When the gate voltage is over 2 volts, essentially no light is detectable. The results clearly demonstrate that this ‘smart’ pixel provides us a simple way to actively modulate the current passing through the nanoFET and nanoLED and hence the output light intensity.

## HIERARCHICAL ASSEMBLY OF NANOSYSTEMS.

**Assembly of functional nanoscale electronic and optoelectronic devices.** The availability of well-defined n-and p-type NW building blocks opens up the possibility of creating complex functional devices by forming junctions between two or more wires. To explore this opportunity, we have investigated n-n, p-p and p-n junctions formed by crossing two n-type, two p-type, and one n-type and one p-type NW, respectively. I-V data recorded on n-n and p-p junctions show linear or nearly linear I-V behavior. These results show that the metal electrodes make ohmic or nearly ohmic contact to the NWs, and hence, will not make significant contributions to the I-V measurements across junctions. In general, transport measurements made across the n-n and p-p junctions also show linear or nearly linear behavior, and allow us to infer two important points

about crossed NW junctions. First, interface oxide between individual NWs does not produce a significant tunneling barrier, since such a barrier would lead to highly nonlinear I-V. Second, that the junction dominates the transport behavior. Overall, our data indicate that crossed NWs make reasonably good electrical contact with each other, despite the small contact area ( $10^{-12}$ - $10^{-10}$  cm $^2$ ) and simple method of junction fabrication.

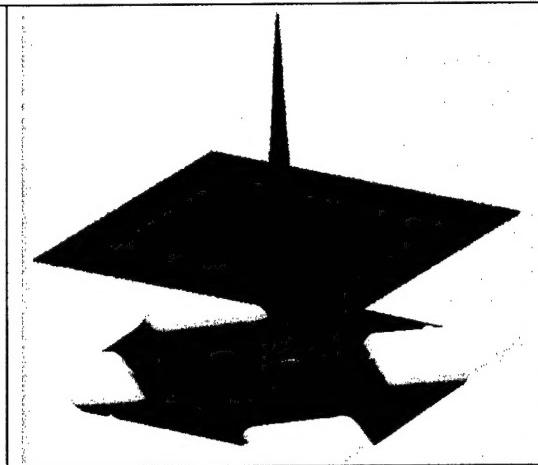
The good contact between crossed NWs suggests that functional devices should be possible, and thus we have explored p-n junctions from crossed p- and n-type NWs. These junctions can be made reproducibly by sequential deposition of solutions of n- and p-type NWs with intermediate drying. Typical I-V data recorded on a crossed NW p-n junction (Fig. 5d) shows linear or nearly linear I-V for the individual n- and p-type NWs components (green & blue curves), which indicates they are ohmically contacted, and current rectification across the p-n junction (red curves); i.e., little current flows in reverse bias, while there is a sharp current onset in forward bias. Significantly, this diode-like behavior is similar to bulk semiconductor p-n junctions, which form the basis for many critical electronic and optoelectronic devices.



**Figure 5.** **a**, SEM image of a crossed NW device. The four arms are designated as A, B, C, D for the simplicity of discussion. **d**, I-V behavior of a p-n junction. The green and blue curves correspond to the I-V behavior of individual n- and p-NWs in the junctions, respectively. The red curves represent the I-V behavior across the junctions.

The above results show unambiguously that we can rationally assemble nanoscale p-n junctions. In direct band gap semiconductors like InP, the p-n junction forms the basis for the critical optoelectronics devices, including light emitting diodes (LED) and lasers. To assess such function in our nanoscale devices, we have studied the photoluminescence (PL) and electroluminescence (EL) from crossed NW p-n junctions. Significantly, EL can be readily observed from these nanoscale p-n junctions in forward bias. A PL image of a crossed NW junction shows two crossed wire-like structures, and comparison of the EL and PL images shows that the position of the EL maximum corresponds to the crossing point in the PL image, thus demonstrating that the light originates from the NW p-n junction (Fig. 6).

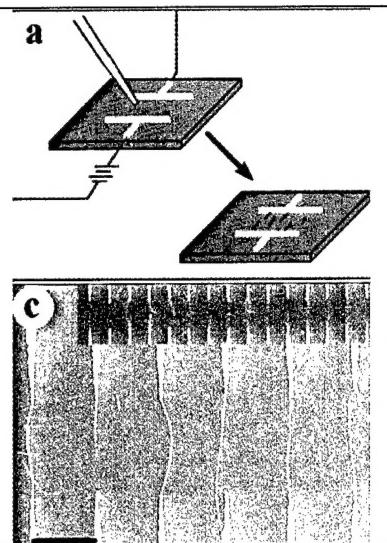
**Figure 6.** Images of an InP nanowire p-n crossed junction and electrically-driven light emission from the junction in forward bias. This device represents the smallest light-emitting diode ever made.



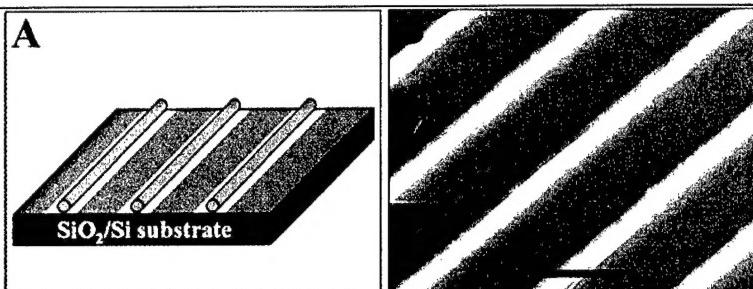
Significantly, our work with other nanowires, such as silicon nanowires, demonstrate that this approach is both general and represents a predictable strategy for assembling a wide range of functional nanoscale electronic and optoelectronic devices. For example, boron and phosphorous-doped silicon nanowires were used as building blocks to assemble rationally three types of semiconductor nanodevices. Passive diode structures consisting of crossed p-type and n-type nanowires exhibit rectifying transport similar to planar p-n junctions. Active bipolar transistors, which consisted of heavily and lightly n-doped nanowires crossing a common p-type wire base, exhibited common base and emitter current gains as large as 0.94 and 16, respectively. In addition, p- and n-type nanowires have been used to assemble complementary inverters. Overall, the facile assembly of key electronic and optoelectronic device elements from well-defined nanoscale building blocks represents a very significant step towards a ‘bottom-up’ paradigm for electronics manufacturing.

**Scalable organization of nanowires and nanotubes.** We have also made very significant progress in the development of general strategies for the scalable assembly of nanowires into nanostructures of increasing complexity. Two methods that we have pursued and published significant results on are (a) electric-field directed alignment and (b) fluid-directed organization. First, we have exploited electric fields (E-field) to align and position individual NWs into parallel and crossed arrays (Fig. 7a). The potential of this approach was first demonstrated by aligning many NWs between parallel electrodes. FE-SEM images show that nearly all of the NWs are aligned perpendicular to the parallel electrodes and along E-field direction. E-field assembly of NWs between an array of electrodes (Fig. 7c) demonstrates that individual NWs can be positioned to bridge pairs of diametrically-opposed electrodes and form a parallel array. In addition, by changing the field direction, the alignment can be done in a layer-by-layer fashion to produce crossed NW junctions. These data show that E-field assembly represents a viable strategy for organizing individual NWs with good directional and spatial control. We believe that highly integrated functional devices will be readily accessible using our NW building blocks in conjunction with this E-field and/or other assembly techniques.

**Figure 7.** Parallel and orthogonal assembly of NWs with E-fields. **a**, Schematic view of E-field alignment. **c**, Spatially positioned parallel array of NWs obtained following E-field assembly using a bias of 80 V. The top inset shows 15 pairs of parallel electrodes with individual NWs bridging each diametrically opposed electrode pair.



Second, we have reported an approach for hierarchical assembly of 1D nanostructures whereby NWs are aligned in fluid flows with the separation and spatial location readily controlled. A typical example of parallel assembly of NWs shows that virtually all the NWs are aligned along one direction; i.e. the flow direction. Examination of the assembled NWs on larger length scales shows that the alignment readily extends over hundreds of micrometers. Indeed, alignment of the NWs has been found to extend up to millimeter length scales, and seem to be limited by the size of the fluidic channels. We have controlled the spatial location of aligned nanowires by utilizing complementary chemical interactions between patterned substrates and NWs (Fig. 5). SEM images of representative experiments (Figs. 8) show parallel NW arrays with lateral periods the same as those of the surface patterns. These data demonstrate that the NWs are preferentially assembled at positions defined by the chemical pattern, and moreover, show that the periodic patterns can organize the NWs into a regular superstructure.

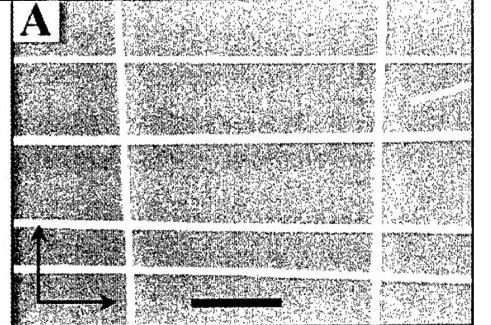


**Figure 8.** Assembly of periodic NW arrays. **(A)** Schematic view of the assembly of NWs onto a chemically patterned substrate. The light gray areas correspond to amino-terminated surfaces, while the dark gray area corresponds to either methyl-terminated or bare surfaces. NWs are preferentially attracted to the amino-terminated regions of the surface. **(B)** Parallel arrays of GaP NWs aligned on a patterned surface. The dark regions in the image correspond to residual PMMA, while the bright regions correspond to the amino-terminated SiO<sub>2</sub>/Si surface. The NWs are preferentially attracted to amino-terminated regions.

Our general approach can be used to organize NWs into more complex crossed structures, which are critical for building dense nanodevice arrays, using the layer-by-layer approach. The formation of crossed and more complex structures requires that the nanostructure-substrate interaction is sufficiently strong that sequential flow steps do not affect preceding ones: we

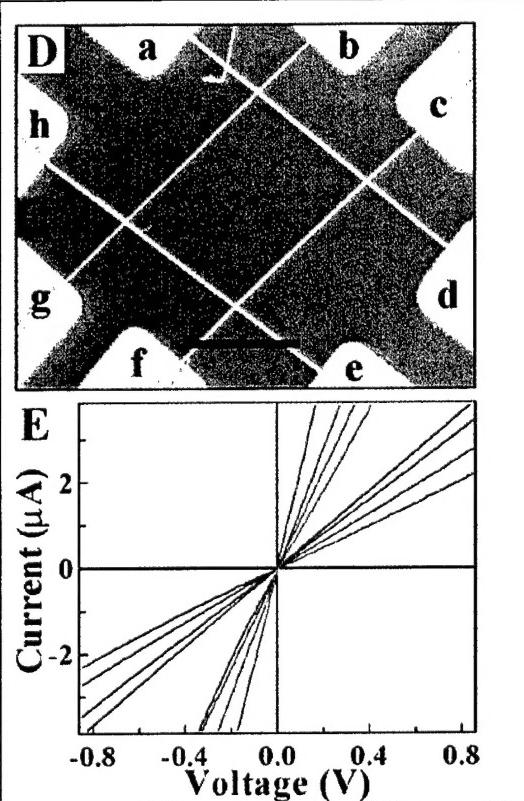
find that this condition can be readily achieved. For example, alternating the flow in orthogonal directions in a two-step assembly process yields crossbar structures (Fig 9). Our results demonstrate that multiple crossbars can be obtained with only hundreds of nanometer separations between individual cross points in a very straightforward, low cost, fast and scalable process. Although the separations between individual NWs are not completely uniform, a periodic array can be easily envisioned using a patterned surface as described above. Significantly, these

**Figure 9.** Layer-by-layer assembly of crossed NW arrays. (A) Typical SEM image of a crossed array of InP NWs obtained in a two-step assembly process with orthogonal flow directions for the sequential steps. Flow directions are highlighted by arrows in the images.



crossbar structures can yield functional devices. For example, it is possible to directly assemble and subsequently address individual nanoscale devices using our approach with n-type and p-type NWs and nanotubes, in which the NWs/NTs act as both the wiring and active device elements. A typical  $2 \times 2$  crossbar array made of n-type InP NWs, in which all eight ends of the NWs are connected by metal electrodes, has been used to demonstrate this point (Fig. 10).

**Figure 10.** Transport measurements on crossed NW arrays. (D) SEM image of a typical  $2 \times 2$  cross array made by sequential assembly of n-type InP NWs using orthogonal flows. Ni/In/Au contact electrodes, which were deposited by thermal evaporation, were patterned by E-beam lithography. The NWs were briefly (3-5 s) etched in 6% HF solution to remove the amorphous oxide outer layer prior to electrode deposition. The scale bar corresponds to 2  $\mu\text{m}$ . (E) Representative I-V curves from two-terminal measurements on a  $2 \times 2$  crossed array. The green curves represent the I-V of four individual NWs (**ad**, **bg**, **cf**, **eh**), and the red curves represent I-V across the four n-n crossed junctions (**ab**, **cd**, **ef**, **gh**).



Transport measurements show that current can flow through any two of the eight ends, and enable the electrical characteristics of individual NWs and the NW-NW junctions to be assessed. The current-voltage (I-V) data recorded for each of the four cross points exhibit linear or nearly linear behavior (red curves), and are consistent with expectations for n-n type junctions. Because single NW/NW p-n junctions formed by random deposition exhibit behavior characteristic of light-emitting diodes (LEDs), we believe it is apparent that our approach could be used to assemble high-density and individually addressable nanoLEDs and electronically more complex nanodevices. In summary, we are very excited by this work since the fluidic assembly approach can be used for organizing other 1D nanostructures into highly integrated device arrays, and thus offers a general pathway for bottom-up assembly of new electronic and photonic nanosystems.

## **CONCLUSIONS.**

These studies have led to the development of the underlying science and technology required to enable the rational design and synthesis of functional nanoscale assemblies and the hierarchical assembly of these functional structures into multifunctional nanosystems. Our work has led to (1) the creation of new nanoscale building blocks that enable novel functional nanostructures, (2) the development of methods to measure and the elucidation of the fundamental nanoelectronic and photonic properties of the nanoscale building blocks that were prepared and (3) the development new, powerful and general methods for the assembly of functional units into nanostructured multifunctional systems.

## **Part Two.**

### **1. Journal publications appearing in print:**

M.S. Gudiksen and C.M. Lieber, "Diameter-Selective Synthesis of Semiconductor Nanowires," *J. Am. Chem. Soc.* **122**, 8801-8802 (2000).

X. Duan, Y. Huang, Y. Cui, J. Wang, and C.M. Lieber, "Indium phosphide nanowires as building blocks for nanoscale electronic and optoelectronic devices", *Nature* **409**, 66-69 (2001).

Y. Huang, X. Duan, Q. Wei and C.M. Lieber, "Directed Assembly of One Dimensional Nanostructures into Functional Networks" *Science* **291**, 630-633 (2001).

Y. Cui and C.M. Lieber, "Functional Nanoscale Electronic Devices Assembled Using Silicon Nanowire Building Blocks," *Science* **291**, 851-853 (2001).

Y. Cui, L.J. Lauhon, M.S. Gudiksen, J. Wang, and C.M. Lieber, "Diameter-controlled synthesis of single-crystal silicon nanowires," *Appl. Phys. Lett.* **78**, 2214-2216 (2001).

M.S. Gudiksen, J. Wang, and C.M. Lieber, "Synthetic Control of the Diameter and Length of Single Crystal Semiconductor Nanowires," *J. Phys. Chem. B* **105**, 4062-4064 (2001).

Y. Cui, Q. Wei, H. Park, and C.M. Lieber "Nanowire Nanosensors for Highly Sensitive and Selective Detection of Biological and Chemical Species," *Science* **293**, 1289-1292 (2001).

J. Wang, M.S. Gudiksen, X. Duan, Y. Cui, and C.M. Lieber "Highly Polarized Photoluminescence and Photodetection from Single Indium Phosphide Nanowires," *Science* **293**, 1455-1457 (2001).

C.M. Lieber "The Incredible Shrinking Circuit," *Sci. Am.* **285**, 50-56 (2001).

Y. Huang, X. Duan, Y. Cui, L. Lauhon, K. Kim, and C. M. Lieber "Logic Gates and Computation from Assembled Nanowire Building Blocks," *Science* **294**, 1313-1317 (2001).

M.S. Gudiksen, L.J. Lauhon, J. Wang, D. Smith, and C.M. Lieber "Growth of Nanowire Superlattice Structures for Nanoscale Photonics and Electronics," *Nature* **415**, 617-620 (2002).

C.M. Lieber "Nanowire Superlattices," *Nano Letters* **2**, 81-82 (2002).

Y. Huang, X. Duan, Y. Cui, and C.M. Lieber "Gallium Nitride Nanowire Nanodevices," *Nano Letters* **2**, 101-104 (2002).

M.S. Gudiksen, J. Wang, and C.M. Lieber "Size Dependent Photoluminescence from Single Indium Phosphide Nanowires," *J. Phys. Chem B* **106**, 4036-4039 (2002).

C.M. Lieber "Nanoscience and Nanotechnology: Building a Big Future from Small Things"  
*Update*. New York, NY: New York Academy of Sciences, October 2002, p.6-9.

**2. Books or book chapters published:**

None.

**3. Presentations:**

June 22, 2001 - The Knowledge Foundation's 2<sup>nd</sup> International Conference on Application & Commercialization of Nanostructured Materials 2001, Chicago, IL  
"Bottom-up Assembly of Nanowires: Technology and Application"

June 24, 2001 - Gordon Research Conference on Analytical Chemistry, Connecticut College, New London, CT  
"Emerging Nanoscale Materials as Molecular Scale Probes for Imaging/Sensing and as Building Blocks for Chemical/Biological Detectors"

June 26, <sup>2001</sup> - 30<sup>th</sup> American Chemistry Society Northeast Regional Meeting, University of New Hampshire, Durham, NH  
"Bottom-up Assembly of Nanoscale Electronics and Optoelectronics from Nanowire Building Blocks"

June 27, 2001- National Academy of Sciences: Studies Committee, Woods Hole, MA  
"Opportunities and Research Priorities for Nanoelectronics"

July 30, 2001- Gordon Research Conference on Clusters, Nanocrystals & Nanostructures, Connecticut College, New London, CT  
"Direct Assembly of Nanowires into Functional Device Arrays"  
**(Yu Huang) – poster session**

July 30, 2001 - Gordon Research Conference on Clusters, Nanocrystals & Nanostructures, Connecticut College, New London, CT  
"Nanowires as Building Blocks for Nanoscale Electronics and Optical Electronics"  
**(Xiangfeng Duan) – poster session**

July 30, 2001- Gordon Research Conference on Clusters, Nanocrystals & Nanostructures, Connecticut College, New London, CT  
"Semiconductor Nanowires: Controlled Growth, Electrical Properties, Assembly of Functional Devices and Chemical-Biological Sensors"  
**(Yi Cui) – poster session**

August 1, 2001- Gordon Research Conference on Clusters, Nanocrystals & Nanostructures, Connecticut College, New London, CT  
"Nanowires as Building Blocks for Nanotechnology"

August 14, 2001 - The Thirteenth American Conference on Crystal Growth & Epitaxy (ACCGE-13), Burlington, VT

"Semiconductor Nanowires: Synthesis, Electrical Transport and Assembly of Functional nanodevices"

September 17, 2001 - Physics Department Colloquium, Harvard University, Boston, MA  
"Nanowires as Building Blocks for Nanoscale Science and Technology"

September 19, 2001 - 2<sup>nd</sup> Georgia Tech Conference on Nanoscience and Nanotechnology, Georgia Institute of Technology, Atlanta, GA  
"Nanowires as Building Blocks for Nanotechnology"

October 3, 2001 - Kilpatrick Lecture Series, Illinois Institute of Technology, Chicago, IL  
"Nanowires as Building Blocks for Nanotechnology"

October 13, 2001 - The Second Dartmouth Molecular Symposium, Dartmouth College, NH  
"Nanowires as Building Blocks for Nanoscale Science and Technology "

October 15, 2001 - Frontiers in Chemical Research, Texas A&M, College Station, TX  
"Nanowire as Building Blocks for Nanoscale Science and Technology"

November 28, 2001 - MRS Fall Meeting, Boston, MA  
"Semiconductor Nanowires As Optoelectronic Building Blocks From Fundamental Physics to Devices"  
**(Mark S. Gudiksen)**

November 29, 2001 - MRS Fall Meeting, Boston, MA  
"Semiconductor Nanowires for Nanotechnology: from Fundamental Chemistry and Physics to Nanoelectronics and Chemical and Biological Sensors"  
**(Yi Cui)**

November 29, 2001 - MRS Fall Meeting, Boston, MA  
"Nanowires as Building Blocks for Bottom Up Assembly Nanoscale Electronics and Optoelectronics"  
**(Xiangfeng Duan)**

November 29, 2001 - MRS Fall Meeting, Boston, MA  
"Directed Assembly of One-Dimensional Nanostructures Into Integrated Device Arrays"  
**(Yu Huang)**

December 2, 2001 - Philips Distinguished Visitor, Haverford College, Haverford, PA  
"Nanowires as Building Blocks for Nanoscale Science and Technology"

December 6, 2001 - US/Germany Joint Meeting on Nanoscale Science and Engineering, Cambridge MA  
"Nanowire Building Blocks for Nanoscale Science and Technology"

February 14, 2002 - American Association for the Advancement of Science Annual Meeting and Science Innovation Exposition, Nanotechnology Seminar, Boston, MA  
Keynote Address: "Nanotechnology: Building a Big Future from Small Things"

April 2, 2002 – Microsystems Technology Laboratories VLSI Seminar at MIT, Cambridge, MA  
“Nanowires as building blocks for Nanoelectronics and Nanophotonics”

April 2, 2002 – 2002 Materials Research Society Spring Meeting, San Francisco, CA  
“Nanowire Building Blocks: Assembly and Functional Device Arrays”  
**(Yu Huang – Poster session)**

April 4, 2002 – 2002 Materials Research Society Spring Meeting, San Francisco, CA  
“Nanoscale Electronics from Assembled Nanowire Building Blocks”  
**(Xiangfeng Duan – Poster session)**

April 11, 2002 – Gomberg Lecture, University of Michigan, Ann Arbor, MI  
“Nanoscience and Nanotechnology: Building a Big Future from Small Things”

April 16, 2002 – Defense Sciences Research Council, New Materials in MEMS, Arlington, VA  
“Nanowires as Building Blocks for Nanoelectronics, NEMS, and Photonics”

April 24, 2002 – 2002 WATT Centennial Lecture, The University of Texas at Austin, Austin TX  
“Nanoscience and Nanotechnology: Building a Big Future from Small Things!”

May 8, 2002 – Swiss Science and Technology Consulate, Cambridge, MA  
“Nanotechnology: Building a Big Future from Small Things”

May 15, 2002 – First International Conference and School on Nanoscale and Molecular Mechanics, Maui, HI  
“Semiconductor Nanowires for Nanotechnologies”  
**(Yi Cui)**

May 25, 2002 – 2002 Glicksman Lecture, Brown University, Providence, RI  
“Nanotechnology: Building a Big Future from Small Things”

June 24, 2002 – 7<sup>th</sup> International Conference on Nanometer-Scale Science and Technology and 21<sup>st</sup> European Conference on Surface Science, Malmö, Sweden  
“Nanowire Superlattices and Core-Shell Heterostructures as Building Blocks for Nanotechnology”  
**(Invited Talk – Mark Gudiksen)**

July 9, 2002 – GRC Chemistry at Interfaces, Connecticut College, New London, CT,  
“Nanowire- and Nanotube-Based Nanostructures”

July 11, 2002 – International Conference on the Science and Application of Nanotubes, Boston College, Chestnut Hill, MA  
“Nanoscale Wires as Building Blocks for Nanoelectronics and Nanophotonics”

August 20, 2002 – 224<sup>th</sup> ACS National Meeting, Boston, MA  
“Integrated Optoelectronics Assembled from Semiconductor Nanowires”  
**(Contributed talk – Yu Huang)**

September 9, 2002 – 175<sup>th</sup> Anniversary of The Royal Institute of Technology at Stockholm, Stockholm, Sweden  
“Building a Big Future from Small Things”

September 24, 2002 – Intel Corporation, Portland, OR  
“Silicon Nanowire Transistors”  
**(Lincoln Lauhon)**

September 28, 2002 – American Physical Society Topical Conference on Opportunities in Biology for Physicists, Boston, MA  
“What Can Nanotechnology do for Biology?”

September 30, 2002 – DARPA Moletronics Principal Investigator’s Meeting, Arlington, VA  
“Design and Hierarchical Assembly of Nanotube-Based Moletronics”

October 8, 2002 – US Army Material Command Conference on Nanotechnology, Natick, MA  
“Nanowires as Building Blocks for Nanoelectronics and Nanophotonics”

November 4, 2002 – Fudan University, Shanghai, China  
“Nanoscale Science & Technology: Building a Big Future from Small Things”

November 4, 2002 – Cambridge Healthtech Institute Conference on Biodefense:Research Technologies and Applications, McLean, VA  
“Highly Sensitive, Real-Time Detection of Biological and Chemical Species Using Integrated Nanowire Sensors”  
**(Yi Cui)**

November 5, 2002 – Zhu Kezhen Distinguished Lectureship, Zhejiang University, Hangzhou, China  
“Nanoscale Science & Technology: Building a Big Future from Small Things”

November 5, 2002 – Zhu Kezhen Distinguished Lectureship, Zhejiang University, Hangzhou, China  
“The Rich and Fundamental Electronic Properties of Carbon Nanotubes”

November 7, 2002 – University of Science and Technology of China (USTC), Hefei, China  
“The Rich and Fundamental Electronic Properties of Carbon Nanotubes”

November 7, 2002 – University of Science and Technology of China (USTC), Hefei, China  
“Nanoscale Science & Technology: Building a Big Future from Small Things”

November 8, 2002 - Tsinghua University, Beijing, China  
"Nanoscale Science & Technology: Building a Big Future from Small Things"

November 15, 2002 – Carnegie Mellon University, Materials Science and Engineering Department Series on Electronic Materials, Pittsburgh, PA  
“Nanowires as Building Blocks for Nanoelectronics and Nanophotonics”

November 19, 2002 – Massachusetts Institute of Technology, A.D. Little Lectures in Physical Chemistry, Cambridge, MA  
“Nanoscience and the Pathway Towards Nanocomputing”

November 21, 2002 – Massachusetts Institute of Technology, A.D. Little Lectures in Physical Chemistry, Cambridge, MA  
“Nanowires as Building Blocks for Nanoscale Science and Technology”

December 4, 2002 – Materials Research Society Fall Meeting, Boston, MA  
“Nanowires as Building Blocks for Nanoscale Science and Technology – Building a Big Future from Small Things”

December 4, 2002 – Materials Research Society Fall Meeting, Boston, MA  
“Integrated Nanowire Based Nonvolatile Random Access Memory”  
**(Contributed Talk – Deli Wang)**

December 4, 2002 – Materials Research Society Fall Meeting, Boston, MA  
“Silicon-Germanium Epitaxial core-Shell Nanowire Heterostructure Devices”  
**(Contributed Talk – Lincoln Lauhon)**

December 4, 2002 – Materials Research Society Fall Meeting, Boston, MA  
“Semiconductor Nanowire Superlattices as Building Blocks for Nanotechnology”  
**(Contributed Talk – Mark Gudiksen)**

December 4, 2002 – Materials Research Society Fall Meeting, Boston, MA  
“Assembly of Nanowire Transistor Based Decoder Arrays”  
**(Contributed Talk – Zhaohui Zong)**

December 11, 2002 – ONR Nanotube Program Review, Newport News, VA  
“Nanostructured Functional and Multifunctional Materials”

December 12, 2002 – First International Conference on Nanoimprint and Nanoimprint Technology, San Francisco, CA  
“Nanoimprint Lithography and Nanoelectronics on Flexible Plastic Substrates”  
**(Poster – Michael McAlpine)**

**4. Patents:**

C.M. Lieber, Y. Cui, X. Duan, and Y. Huang, "Doped Elongated Semiconductors, Growing Such Semiconductors, Devices Including Such Semiconductors and Fabricating Such Devices", 09/935,776, U.S. patent pending; PCT/US01/26298, International patent pending; EPO 1966109.9 European patent pending; 10-2003-7002636 South Korean patent pending; 90120587 Taiwan patent pending; patents also filed in Singapore, Hong Kong, Mexico, Japan, China, Canada and Australia.

C.M. Lieber, H. Park, Q. Wei, Y. Cui, and W. Liang, "Nanosensors", 10/020,004, U.S. patent pending; PCT/US01/48230, International patent pending.

C.M. Lieber, X. Duan, Y.Cui, Y. Huang, M.S. Gudiksen, L. Lauhon, J. Wang, H. Park, Q. Wei, W. Liang, D.C. Smith, D. Wang and Z. Zhong, "Nanoscale Wires and Related Devices", 10/196,337, U.S. patent pending; International Patent Publication Number WO 2004/038767, published May 6, 2004.

C.M. Lieber, X. Duan, Y. Huang, and R. Agarwal, "Nanoscale Coherent Optical Components", 10/624,135, U.S. patent pending; 10/734,086 U.S. Continuation Patent Pending; International Application No: PCT/US03/22753, International Publication Number WO 2004/010552, published on January 29, 2004.

**5. Honors, awards or prizes received during reporting period:**

Charles M. Lieber, Harvard University, New York Intellectual Property Law Association Inventor of the Year (2003).

Charles M. Lieber, Harvard University, Scientific American Award in Nanotechnology and Molecular Electronics (2003).

Charles M. Lieber, Harvard University, Nelson W. Taylor Award, Pennsylvania State University (2003).

Charles M. Lieber, Harvard University, New York Intellectual Property Law Association Inventor of the Year (2003).

Charles M. Lieber, Harvard University, World Technology Award in Materials (2003).

Charles M. Lieber, Harvard University, APS McGroddy Prize for new Materials (2003).

Charles M. Lieber, Harrison Howe Award (2002).

Charles M. Liber, Honorary Professorship, Tsinghua University (2002).

Charles M. Liber, Honorary Professorship, University of Science and Technology of China (2002).

Charles M. Liber, Honorary Professorship, Fudan University (2002).

Charles M. Liber, Honorary Professorship, Zhejiang University (2002).

Charles M. Lieber, Harvard University, Member, American Academy of Arts and Sciences AAAS (2002).

Charles M. Lieber, Harvard University, MRS Medal (2002).

Charles M. Lieber, Harvard University, Fellow of the World Technology Network (2002).

Charles M. Lieber, Harvard University, Feynman Prize in Nanotechnology (2001).

Charles M. Lieber, Harvard University, Fellow of the International Union of Pure and Applied Chemistry (2000);

Charles M. Lieber, Harvard University, Editorial Board, *Applied Physics Letters*.

Charles M. Lieber, Harvard University, Editorial Board, *Journal of Applied Physics*.

Charles M. Lieber, Harvard University, Editorial Board, *Journal of Nanoscience and Nanotechnology*.

Charles M. Lieber, Harvard University, Editorial Board, *Journal of Physical Chemistry*.

Charles M. Lieber, Harvard University, Advisory Editorial Board, *Journal of Physics: Condensed Matter*.

Charles M. Lieber, Harvard University, Editorial Board, *NanoLetters*.

Charles M. Lieber, Harvard University, Editorial Board, *Virtual Journal of Nanoscale Science and Technology*, American Institute of Physics

Charles M. Lieber, Harvard University, Advisory Board, Advances in Nanoscale Materials and Nanotechnology, book series.

Charles M. Lieber, Harvard University, Editorial Advisory Board, Encyclopedia of Nanoscience and Nanotechnology, Fullerenes, Nanotubes and Carbon Nanostructures.

Charles M. Lieber, Harvard University, Advisory Board, Nanotechnology Opportunity Report.

## **6. Technology Transfer:**

A broad patent application has been filed relating to the synthesis of semiconductor nanowires superlattices consisting of axially-modulated structures, and relating to the novel electronic and photonic device characteristics of these new nanoscale building block materials. This intellectual property has been licensed exclusively by a new company, NanoSys Inc., that is focused broadly on using nanowire nanotechnology to enable applications in biotechnology, electronics and photonics.